DESY SPECIFICATION OF WELDED 1.3 GHz SUPERCONDUCTING RESONATORS FOR TTF-FEL

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VERSION A

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1 INTRODUCTION

This specification describes fabrication details of the superconducting resonators for the acceleration of electrons in the TTF-FEL. TTF-FEL is an extension of the experimental linear accelerator TTF (TESLA Test Facility) and will mainly serve as a FEL radiation source.

The resonator is joined from deep drawn half cells and special end sections entirely by electron beam welding. Correct cell form is important to reach the desired resonant frequencies (accelerating mode and some important higher frequency resonances) at specified cell- and resonator lengths.

The HOM-coupler is described in this specification and in parts-list 993 2214/0.000 and drawings contained and drawings contained therein.

The accuracy of form of single cells and the complete 9-cell structure as required by drawing 093 2214/0.000 call for accurate deep drawing of half cells, and suitable weld preparation and control of welding parameters.

This specification is an update of the former DESY specification of 24 welded 1.3 GHz Superconducting Resonators for TESLA Test Facility TTF. There are changes which are based on the experience with the last cavity production: tight frequency control of half cells and dumb bell, more tight welding conditions, compensating slight contour deviations of the half cells by trimming the equator region at the stage of dumb-bells, more chemical cleaning of half cells and HOM parts, more strict quality control on mechanical tolerances and an extended description of cleaning and handling necessities.

2 FABRICATION DRAWINGS

The DESY drawings are listed with actualization index in Appendix "13.12". Upon any change in a drawing, it will receive a new actualization index and a new drawing list will be issued which invalidates earlier issues.

On the basis of the DESY drawings the contractor produces his own fabrication drawings for the resonator. The dimensions in these drawings must allow for the material removal by etching and weld shrinkage such that after etching and welding the tolerances specified by the DESY drawings are achieved. He also prepares prescriptions for chemical treatment and controls of drawings of tools and fixtures for production. For the content of the documents he prepares the contractor is responsible exclusively.

DESY is furnished with a full set of the above mentioned fabrication documents at least 2 weeks prior to their use for production. DESY will check if the specified characteristics of the resonator may be achieved with these documents. Possible comments from DESY pertaining to these documents are without any liability. DESY finally receives a set of the documents actually used for production. In view of the still ongoing development work, DESY may wish to modify details of the current design of the resonator. Such modifications will be carried out by the contractor.

3 SUPPLY OF MATERIAL

3.1 Nb QUANTITY

The niobium stock is furnished by DESY. Appendix "13.1" lists all parts needed to fabricate one 9-cell resonator. DESY delivers this amount per cavity plus a reserve of ca. 10 %. If the contractor requires still more stock, he may buy more from DESY. All stock for the half cells is eddy current scanned by DESY to detect and sort out material with inclusions of foreign materials or other defects. Any left over niobium stock and scrap pieces of more than 20 grams will be returned to DESY with the last resonator shipment.

3.2 INCOMING INSPECTION

Upon receipt, the contractor will inspect the niobium stock for conformity with specification. In case of nonconformity DESY will inspect the material at the contractor's plant and replace the material.

3.3 SHEET MATERIAL FOR HALF CELLS

All sheet material for the half cells has been eddy current scanned at DESY. The later "outer" surface is marked by DESY by methods to be agreed on by the contractor. This mark should be visible after deep drawing, welding and chemical cleaning. The opposite sheet surface is the "inner" surface which carries the superconducting surface current. This surface shall not be contaminated by any handling procedure (see Appendix "13.4, 13.10")

4 PRODUCTION OF PARTS

4.1 NbTi FLANGES (DRAWING NO. 393 2214/0.020, 393 2214/0.021, 3932214/0.022)

All flanges (2 x beam pipe, 1 x pick up, 1 x input coupler, 2 x output of HOM coupler) are made from NbTi. A rod of diameter 147 mm NbTi material is furnished by DESY. The smaller diameter flanges are made from inner the cut out of the large flanges. The sealing surface must have a very good surface quality (N6) and must be free of any scratches, especially radial ones. Therefore the surface finish must be done with a method which removes the material tangential to the circle of the sealing area. The finished sealing surface shall be protected by plastic half cells (soft polyvinyl chloride is acceptable). The removal rate for NbTi by the standard chemical etching mixture (see App. "13.3") is a factor of two larger as compared to niobium.

The connection of the NbTi flanges to the Nb tube was done in the last production by EB welding from the front side (sealing surface) of the NbTi flange. The surface finish of this weld was not always smooth, as required. Furthermore there was a gap between the NbTi flange and the Nb tube at the backside of the flange. Therefore it may be considered by the contractor to carry out butt welding between the NbTi flange and the Nb tube at the backside of the NbTi flange. The contractor is requested to reconsider the welding procedure of all subgroups containing NbTi flanges and consult with DESY on the welding procedure.

4.2 BEAM TUBES (DRAWING NO. 393 2214/B.006, 393 2214/C.005)

Seamless tubes of length 105 mm (endtube right) and of length 140 mm (endtube left) are furnished by DESY.

4.3 HOM COUPLER PARTS (DRAWING NO 993 4417/0.001, 293 4417/0.000, 393 4417/0.001, 393 4417/0.002)

The HOM coupler will carry sizeable RF surface currents (inner surface of "coupler housing", "F part"). Therefore these parts must be treated with the same care as the inner surface of the half cells and dumb-bell. The inner surface of the coupler housing as delivered by DESY has a smooth, scratch free surface. This surface shall not be contaminated by other material or scratches. The surface of the "F part" must fulfill the surface conditions as described for the inner surface of the half cells and dumb-bells.

4.4 STIFFENING RING (DRAWING NO 493 2214/A.002)

Stiffening rings are welded to the outer side of the half cells when completing the dumb-bells. It is necessary to assure a 100 % penetration weld in order to avoid cracks at the backside of the stiffening rings. This would weaken the mechanical strength and risk contamination by chemistry, since the acid cannot be removed out of the cracks. The geometry of the welding cut at the stiffening ring and at the mating part of the outer surface of the half cells must be chosen to assure the quality of the desired welding.

4.5 PICK UP AT BEAM PIPE AND HOM COUPLER (DRAWING NO 493 2214/0.009)

The small pick up tube (outer Ø 12 mm) is EB welded to the large diameter beam pipe. It is important to produce a 100 % penetration weld. In case of gaps or cracks at the inner surface, acid will penetrate during etching and contaminate that region. In some of the recently produced cavities inner grinding was applied to eliminate those cracks. This method cannot be accepted, because it is very difficult to inspect this area for any remaining small crack. Therefore a welding geometry has to be chosen by the contractor which assures a full penetration welding seam.

4.6 BORDSCHEIBE (DRAWING NO 493 2214/B.004, 493 2214/C.003)

The "Bordscheibe" is the connecting part between Nb cavity and Ti tank. For a tight fit of the connecting parts to the Ti tank, it is important to establish an only small planarity error at the outer shoulder (Ø 186 mm and Ø 194.8 mm, please note that the "Bordscheibe" at the right and left endtube are of different outer diameter). This is established by cutting the shoulder (3 mm) after finishing all weldings to the Bordscheibe. For the welding to the Ti tank it is required that a cylindrical part (Ø 186 mm and Ø 194.8 mm) of at least 0.5 mm remains in order to avoid a blow through of the welding beam.

4.7 CONNECTING FLANGE ("ANSCHLUSSFLANSCH", DRAWING NO 393 2214/0.002)

The connecting flange will locate precisely the tuner assembly and serve as reference for alignment of the cavities. Therefore a tight tolerance, as given in the drawings, is necessary. As consequence the final machining must be done after finishing all welding to avoid deformation of the connecting flange.

5 PRODUCTION OF SUBGROUPS

5.1 HOM COUPLER

The "F-part" is cut from a 8.5 mm thick RRR 300 Nb sheet. In order to save Nb material, the "F-part" should be arranged in an interlaced geometry. Cutting the Nb material should not deteriorate the bulk properties. Water cutting or spark erosion can be used for this purpose. A removal of the damaged surface layer of 0.5 mm is necessary after the last mechanical treatment. The "F-part" must have a smooth, defect free and scratch free surface.

Before welding the "F parts" to the coupler housing, both parts must be cleaned by removing 20 μm by the standard chemistry for Nb (see App. "13.3"). Cleaning with ultrapure water, drying and storage shall be done according to conditions described in App. "13.3, 13.4". If welding cannot be carried out within 8 hours after the chemical cleaning, another flash of 3 μm chemical etching is necessary immediately before welding.

5.2 END GROUPS

The assembly is called: "Endhalbzelle-Endrohr-Einheit" (EEE), and shown for the cavity version with welded HOM coupler in drawings 293 2214 B.000 (with long end tube) and 293 2214 C.000 (short end tube). The two end half cells as well as the two end tubes of the resonator are different.

No more than 8 hours before welding the surfaces of the end tubes and end tube sections ("Endrohrstueck") are degreased, ultrasonic cleaned, etched by 3 μm, rinsed with ultrapure water, dried and stored described in section "13.3, 13.4".

The resonance frequency of the end half cells (before welding to the connecting flange) has to be measured according to "6.3". At this stage the end half cells are longer by 1 mm at the equator (in addition to the expected welding shrinkage at equator and iris). Another frequency measurement shall be done after welding the connecting flange plus part of the beam tube to the end cell. As in the case of dumb-bell frequency measurement, possible contour changes by the welding procedure will be uncovered hereby. The frequency measurement will determine the amount of trimming at the equator. The end tube is joined via the end tube section to the iris of the end half cell by welding from the inside.

The reference and connecting flange ("Anschlussflansch") among other things serves the same function as the stiffening ring of the dumb-bell and carries the head disk ("Bordscheibe"). The short tube section ("Endrohrstueck") is made from the same stock as the long end tube. For all welding of the EEE, "General electron beam welding requirements" ("13.6") needs to be observed.

The finished sealing surfaces of the above mentioned flanges shall be protected by plastic caps (soft polyvinyl chloride is acceptable) at all times, except for flange dimensions measurements and inspection of finish of sealing surfaces.

After finishing all welds, the reference and connecting flange and head disc are machined, with the EEE held from the inner surface of the half cell, analogously as described in "6.2".

As pointed out in "4.6", the cylindrical part of the shoulder at the head disc (Ø 186 mm, Ø 194.8 mm) should have a minimum width of 0.5 mm. The exact contour of the connecting flange should be checked with an original assembly ring of the tuner. DESY will supply this assembly ring.

Finally, the EEE is chemically cleaned ("13.3") with 20 μm of removal (the NbTi flanges must be protected from the acid), then inspected for defects, and treated in all respects like the dumb-bell (Anodising and grinding "6.6").

5.3 FREQUENCY MEASUREMENT OF END GROUPS

The frequency of the end half cells is measured according to "6.3" and "7.3", steps 4 to 8. After welding the end half cell to the end group the frequency of this unit is measured. Afterwards the equator is trimmed to length accordingly.

6 PRODUCTION OF CELLS

6.1 DEEP DRAWING OF HALF CELL

From the square plates provided, discs with or without a central hole are produced (depending on choice of contractor) and then deep drawn into half cells. It must be assured, that the marked sheet surface will be the outer half cell surface after deep drawing. The "inner" surface of the Nb sheet must be handled with greatest care to avoid any contamination and damage by the deep drawing process. One of the scrap corners of each plate is marked identically to the half cell made from the plate, and stored in a sealed plastic bag for possible future material tests.
For establishing the form of the deep-drawing tooling the spring-back and thickness tolerance of the niobium sheet material has to be taken into consideration. It is also important that at the end of the deep-drawing operation the inner surface of the half cell is everywhere in intimate contact with the mandrel. Possible seizing marks or other damage on the inner resonator surface must be strictly avoided. The surfaces of the tooling and the niobium disc must be carefully cleaned prior to each deep drawing operation, such that no dirt, metal particles or other matter can become embedded in the niobium surface. As stated before, any lubricants or deep-drawing foil used must be completely removable by the ensuing cleaning operations.

Further, the form of deep-drawing tooling must also take into consideration the change of mechanical dimensions caused by etching the dumb-bell. For first deep-drawing tests copper has been successfully used. As material for the mandrel, aluminum alloy, hard anodized, is recommended.

6.2 PREPARATION OF HALF CELLS FOR DUMB-BELL WELDING

The weld preparation of the half cells has three main purposes:

- It must allow assembly of half cells into a resonator with the accuracy required by drawing 093 2214/0.000 while considering weld shrinkage and material removal by etching. It may also be so shaped as to center the half cells with respect to each other.
- It must produce correct and uniform wall thickness at iris (smaller diameter) and equator (larger diameter) to avoid locally burning through during welding and to achieve a smooth weld surface on the inner surface of the resonator if welding proceeds from the outside.
- It must allow longitudinal and radial locating of the prefabricated stiffening rings ("Versteifungsringe") in proper relation to the inner surface of the half cell.

It is advisable to machine **in one clamping** in a lathe all the weld preparations of the half cell including that for the stiffening ring. For this the half cell is located on a fixture from its inner surface which must not be damaged thereby. By this method unroundness at the equator can be eliminated *during* the machining operations, and the various weld preparations can be prepared at the proper location with respect to the contour of the inner surface of half cell.
At this stage the iris is cut to a length which takes into account the welding shrinkage. At the equator, the half cell is longer by 1 mm plus welding shrinkage. The equator will be cut to the right length after frequency measurement of the dumb-bell (see section "6.5") again taking into consideration the weld shrinkage. The details of the weld preparations contemplated by the contractor need to be approved by DESY.
The finished half cells must be inspected with respect to inside contour and the proper relation of the various weld preparations to it. Use of templates, among other tools, is acceptable for this purpose.

At a rate of 5 % of the half cells, the inner contour has to be measured by 3D technique. The samples are selected randomly. All end half cells have to be measured by the 3D technique.

6.3 FREQUENCY MEASUREMENT OF HALF CELLS

After degreasing the half cells, the resonant frequency is measured for all parts. Equipment and manpower is supported by DESY. This frequency measurement will deliver information about

- the accuracy of the contour of the half cells by the average value of the resonant frequencies,
- the reproducibility of shaping the half cells by the spread of resonant frequency,
- the status of the half cells before dumb-bell welding.

Non acceptable deviations of the resonant frequency of half cells or a too large spread in frequency must be reduced by modifying tools or forming parameters.

6.4 WELDING OF DUMB-BELL

The half cells are ultrasonically cleaned, etched 20 μm (one side) rinsed, dried and stored as specified in "13.2, 13.3, 13.4". No longer than 8 h before E.B. welding are the niobium parts etched 3 μm (one side), rinsed, dried and stored as specified in “13.4”.

Two standard half cells (“Normalhalbzelle”, drawing 193 2214/A.001) are welded together at their irises into a “dumb-bell”. The selection of two half cells for one dumb-bell is guided by the evaluation of the resonance frequency measurement "6.3" to yield an average frequency as close as possible to the design value. The requirements of welding conditions (“13.6”) have to be observed. It is recommended that this weld receives its smooth surface on the inside by welding from inside. To the dumb-bell is welded the stiffening ring (drawing 493 2214/A.002). Execution and sequence of welds while considering weld shrinkage have to be chosen as to produce dumb-bells with which the cell form tolerance in drawings 093 2214/0.000 is achieved. If needed, form correction by plastic deformation of dumb-bell is acceptable after coordination with DESY.

The execution of a full penetration weld at the stiffening ring might result in a slight distortion of the cavity shape. Just underneath the weld of the stiffening ring there might be a slight elevation. This local distortion must be investigated by test welds and will be judged by DESY for approval.

It seems advisable to use a welding fixture that ensures parallelity of the equator planes of the 2 half cells to be joined, while leaving axial freedom to accommodate weld shrinkage. The fixture must not touch the inner half cell surface.

The dumb-bell is finally inspected for correct dimensions and weld characteristics.

6.5 FREQUENCY MEASUREMENT OF DUMB-BELLS

After completion of the dumb-bells (iris and stiffening ring welding) the resonance frequency is measured again. The evaluation of this measurement will determine the amount of trimming at the equator to achieve simultaneously the correct length and the correct frequency of the finished resonator. It also serves as a measure of contour change and reproducibility of iris and stiffening ring welding.

Both ends of the dumb-bell will be cut to the length determined by the evaluation of the frequency measurement done at DESY. For the trimming the dumb-bell is located on a fixture from the inner surface which must not be damaged thereby. By this method both equatorial planes will be cut parallel.

6.6 ANODISATION AND GRINDING OF DUMB-BELLS

Next, the dumb-bell is degreased, ultrasonically cleaned, etched by 20 μm, rinsed and dried as required in “13.2, 13.3, 13.4”. An anodization is now made ("13.7"). The RF-surface is inspected jointly with DESY and, where deemed to be defective ground with abrasive material according to appendix "13.8",. If no grinding needs to be carried out, the dumb bell is stored in accordance with appendix “13.4”. The anodization will be removed by the 3 μm pre-welding etching.

Grinding should be avoided as much as possible. If, however, grinding has to be applied, the dumb bell is etched another 20 μm, rinsed, dried, anodized again, and stored as prescribed in appendix "13.2, 13.3, 13.4”. If again surface defects are detected, another sequence of grinding, etching and anodisation is necessary.

7 WELDING OF CAVITY

7.1 WELDING OF DUMB-BELL TO DUMB-BELL

8 dumb-bells, a left EEE and a right EEE are joined in accordance with “13.6” with equator-welds from the outside. The contractor may also elect to execute the equator welds from the inside. Please note that a repair of an equatorial weld defect cannot be accepted (see "13.6").

Out-of-roundness of half cells at the equator, if present, results in a deviation from planarity of the weld preparation at the equator. The planarity, necessary for avoiding gaps at weld seam, can be achieved by using a tool that keeps the half cells round during tack welding.
Also in these welds, niobium vapor must be prevented by suitable shields from being deposited on yet unwelded weld preparations. Since a complete shielding is very difficult it is requested to chemically clean (3 μm) the neighboring two equator areas before the next welding.

7.2 WELDING OF END GROUP TO DUMB-BELL

Welding of the end group to the dumb-bell is done in the same way as welding dumb-bell to dumb-bell. Please note, that a repair of a weld defect of the equatorial weld cannot be accepted (see "13.6").

7.3 SEQUENCE OF HALF CELL AND DUMB-BELL TREATMENT, CLEANING AND WELDING

In the following overview the sequence of half cells, dumb-bell and cavity body fabrication is summarized.

1. Optical, mechanical inspection of Nb sheets

2. Cutting Nb sheets to disc

3. Deepdrawing of half cells ("inner side" of half cells!)
4. Cutting half cells to length $L = L_{nom} + \delta L_{equ} + \delta L_{iris} + 1$ mm (L_{nom} = nominal length, $\delta L_{equ.}$ = welding shrinkage at equator, δL_{iris} = welding shrinkage at iris + stiffening ring)
5. Prepare welding steps at iris and stiffening ring
6. Degreasing, ultrasonic cleaning, rinsing
7. Frequency measurement, selection of half cells for dumb-bells
8. 20 μm chemical cleaning of half cells (inner and outer surface), rinsing, storage
9. 3 μm chemical cleaning at iris area, rinsing
10. Welding of iris within 8 hours after step 9
11. Welding of stiffening ring
12. Frequency measurement of dumb-bells
13. Cutting equators of dumb-bells to right length according to frequency measurement ("12"), machining welding area (drawing No 393 2214/A.000)
14. Degreasing
15. Frequency measurement of dumb-bells, selection of dumb-bells for welding sequence of cavity
16. Degreasing of dumb-bell
17. 20 μm chemical cleaning of dumb-bells
18. Anodising of dumb-bells
19. Inspection of "inner" dumb-bell surface for defects, if OK, continue at step 23
20. Grinding of defects
21. 20 μm chemical cleaning of dumb- bells for cleaning of surface from grinding dirt
22. go back to step 18
23. Storage of dumb-bell
24. 3 μm chemical cleaning at equator region of the dumb-bell to be welded
25. Welding of two dumb-bells at equator within 8 hours after step 24
26. Repeat step 24 with longer cavity section

8 FINAL TEST OF CAVITY

8.1 LEAK CHECK

Before lowering the internal pressure, the resonator must be constrained against becoming shorter and thus being permanently deformed, by fixing its connecting flanges (“Anschlussflansche”) to external braces. Silicon grease must be strictly avoided.

The finished resonator is subjected to a leak test. The prescribed leak-tightness of

$$\leq 1\times 10^{-10} \text{ mbar l/s}$$

must be determined with the sensitivity of the helium leak tester such that full range of its instrument corresponds to

$$\leq 1\times 10^{-9} \text{ mbar l/s}$$

A plot of the indication of the leak tester as function of time shall be made over ca. 5 min before and ca. 5 min after application of ca. 1 bar helium, with time of application of He marked in the plot. This plot shall be included in the quality control documentation.

Repair of leaks requires in all cases prior approval of DESY as to the method, and possible risks.

8.2 MECHANICAL MEASUREMENT

Dimensions, inner surface, welds and other features of the resonator are inspected as per paragraph "12".

All results of measurements and inspections are recorded in a protocol and sent to DESY **prior** to shipment of resonator.

9 PACKING AND SHIPPING

The degreased resonator, with all plastic flange caps in place, is sealed into a clean polyethylene foil and mounted in a transport box. The resonator is to be fastened only on the **2nd and 8th cell** and must be secured against axial displacement. Transport is by truck or airplane (rail excluded).

10 TIME SCHEDULE

A reliable time schedule has to be provided by the contractor when signing the contract. It must contain reasonable details to follow closely the production as well as state milestones, e.g. frequency measurement of half cells and dumb-bells, start of welding the cavity body and delivery of individual resonators.

11 PROGRESS REPORT

The contractor shall submit a monthly progress report to the DESY technical representative. The progress report shall provide full details concerning the contractor's progress during the previous month. The progress report shall be submitted until the 15th day of the following month in which progress is reported.

12 QUALITY ASSURANCE DOCUMENTATION

Appendix "13.12" lists tables of quality assurance measurements. The individual parts (see section "4"), subgroups (see section "5") and cavity body components (see section "6" and "7") have to be measured. The method of measurement is proposed by the contractor and must be agreed on by DESY. Any nonconformity of parts, subgroups or cavity body items with the specification has to be reported to DESY prior to continuation of the production. DESY will decide whether to use or reject the part.

13 APPENDIX

13.1 LIST OF PARTS

Material (Quality)	Delivered amount	Material	Purpose
RRR 300	18	Nb sheets 265 x 265 x 2.8	Half cell
RRR 40	2	Nb rings 220 x 100 x 5 ± 0.2 mm	Bordscheibe (disk)
RRR 40	Length 217 mm	Nb sheets 3 ± 0.15 x 360 x fabrication length (> 2134 mm)	Stiffening ring
RRR 300	Length 50 mm	Nb sheet 1000 x 300 x 8.5 ± 0.2 mm	Inner part, coupler
RRR 40	Length 50 mm	Nb rod ∅ 20 x 700	Forged bar, antenna neck
RRR 300	1	Seamless Nb tubes I∅ 78 ± 0.2 x 3 ± 0.3 x 105 mm	Endtube right
RRR 300	1	Seamless Nb tubes I∅ 78 ± 0.2 x 3 ± 0.3 x 140 mm	Endtube left
RRR 300	1	Seamless Nb tubes I∅ 40 ± 0.15 x 2.5 ± 0.15 x 155 mm	Maincoupler port
RRR 300	2	Forged Nb rings 135 x 75 x 27 mm	Connecting flange Type "D"
RRR 300	2	Pre-formed part according to DESY MPL drawing 393 4417/0.001	Coupler housing
NbTi	∅ 147 mm, length 20 mm	Rundstab Nb 55% Ti	Beam pipe flange
Nb Ti	"	Rundstab Nb 55% Ti	Input coupler flange
NbTi	"	Rundstab Nb 55% Ti	HOM port flange
NbTi	"	Rundstab Nb 55% Ti	Pick up antenna flange

13.2 DEGREASING, ULTRASONIC CLEANING, DRYING

Degreasing and ultrasonic cleaning with "Ticopur" or equivalent, followed by rinsing in de-ionized, filtered (0.2 μm particle size) water, precedes all etching operations. Rinsing is done until a resistivity of 10 MΩcm is reached. Hot water (temperature about 60 ^{0}C) is preferred for more intense cleaning action. For selection of baths for degreasing and ultrasonic cleaning the contractor will contact DESY. Drying is carried out in laminar airflow in a clean room of class 1000 or better. The parts must be supported in places well away from the weld preparations and the RF surfaces to avoid drying stains there.

13.3 CHEMICAL CLEANING, RINSING, DRYING

Generally, all etching operations are carried out with the niobium part immersed in the acid mixture, i.e. over the entire surface. The acid mixture consists of HF (48 % conc.), HNO_3 (65 %) and H_3PO_4 (85 conc.) in the volume ratio 1 : 1 : 2, respectively. All acids are p.a. grade. The removal rate is roughly 1 μm/min for fresh acid at 15 ^{0}C, but depends on agitation as well as niobium content and temperature of acid mixture. Before etching resonator parts, a test etching must be made. After etching, the parts are quickly (within max. 15 sec) immersed in a rinsing bath. At no time during etching and transfer to the rinsing bath may the acid temperature be permitted to exceed 20^{0}C.

The acid mixture is replaced when its niobium content reaches 10 g/l, corresponding to an etch rate of about 0.5 μm/min.

For all etching operations there shall be recorded in a protocol: Part type and serial number, bath temperature, duration and thickness removed (determined by weighing of at least one sample out of each batch).

Removal of thickness always is understood to refer to one surface only.

The etched parts are rinsed with de-ionized, to 0.2~μm particle size filtered water until resistivity of 10 MΩcm is reached.

Drying is carried out in laminar airflow in a clean room of class 1000 or better. The parts must be supported in places well away from the weld preparations and the RF surfaces to avoid drying stains there.

13.4 HANDLING AND STORAGE CONDITIONS

Contact of the niobium surfaces with substances that the cleaning and etching processes described in “13.2, 13.3” will not completely remove must be prevented. Such forbidden materials include silicone products, chemically very stable plastics such as Teflon, fingerprints and others. They can disturb etching processes and limit RF performance. General precautions against contamination of the Nb parts include use of suitable lint free gloves, keeping work areas and tools used in clean condition, and protection against dust during storage and assembly of cavity components.

Anodization of niobium surfaces serves for the detection of possible surface defects and handling pollution (e.g. fingerprints). The details of the anodization process are described in appendix "13.7" Cleaned parts are protected during storage and transport from dust, contact with “forbidden” materials and mechanical damage. For this purpose clean, closed polyethylene boxes have proven useful.
The parts should not be supported on weld areas. The half cells should be supported on the outer surface. The dumb bells must be stored with horizontal axis.

13.5 WELDING PREPARATION

Before welding, all parts must be cleaned by 3 μm chemical etching at the welding area. Welds at the equator and iris of cells and at the HOM coupler parts will be exposed to high magnetic or electric fields. Therefore absolutely clean conditions must be assured during welding. These parts must undergo a chemical cleaning of 20 μm after the last mechanical treatment. Another 3 μm chemical cleaning is necessary if the time between last chemical cleaning and welding exceeds 8 hours. Touching the weld preparation area after the last cleaning must be strictly avoided. Especially storing the half cells or dumb-bells with the equator/iris weld preparation area touching the storage table is not allowed. Also wiping the welding step with some alcohol soaked "dust free" cloth must be avoided. A last cleaning of the welding step from dust by blowing with clean and dry nitrogen gas is recommended. Ionized gas may be helpful to remove dust.

13.6 GENERAL ELECTRON BEAM WELDING CONDITIONS

To prevent oxidation and other contamination of weld preparations, welding shall generally commence within the same work shift in which the parts were cleaned, etched, rinsed and dried.

The pressure in the welding chamber has to be less than 5×10^{-5} mbar during welding. The welding chamber shall be vented with clean nitrogen only after the temperature of the niobium part has dropped to 100 ^{o}C at the hottest spot.

All welds must have full penetration, be smooth and of uniformly wide root on the inside surface of resonator and must neither protrude nor stay back by more than 0.1 mm with respect to the neighboring surface. Some larger protrusion might occur locally underneath the stiffening ring welding (see section "6.4"). Welding from the inside (RF-side) is recommended, wherever possible. Wiggling the electron beam according to a suitable pattern has been found to be very useful in producing uniformly wide and flat roots and to reduce risk of burning holes. By suitable shields niobium vapor from welding must be prevented from contaminating weld preparations elsewhere.

The contractor shall, after optimization of welding parameters, demonstrate by test welds to DESY that the RRR in the welds and weld overlaps is not degraded by more than 10 % over that of the unwelded niobium. No cracks, pores, inclusions of foreign materials or other defects are allowed in welds. DESY will check that these requirements are met on test- and production welds by eddy current- and other methods. During the weld tests the welding-chamber gas is analyzed with a mass spectrometer (DESY can assist with equipment and personnel). The final welding parameters for production are subject to approval by DESY.

The experience with the earlier cavity production has provided clear evidence, that there exists no appropriate procedure to repair a hole in the equatorial weld. Although the visual appearance of a repaired weld looks good, the RF performance of such a cell is degraded: quenches at the repaired area limit the accelerating gradient far below the design value of 25 MV/m. Therefore a repaired equatorial weld cannot be accepted. In such a case the contractor has to inform DESY and propose a procedure to cut the damaged cell and replace it by a cell which is free of welding defects. The repair procedure has to be agreed on by DESY but will be carried out at the contractor's risk and cost.

Any repair of a weld other than at the equator, contemplated by the contractor, requires in each instance prior approval of the methods by DESY.

13.7 ANODISING

13.7.1 INTRODUCTION

Anodization means the electro-chemical oxidation of metal surfaces like aluminum, titanium or niobium. It results in a colorated surface depending on the experimental conditions. For the production of niobium cavities the better contrast of the colorated surface allows the detection of defects and inclusions of foreign material.

13.7.2 PROCESS

The electro-chemical process of anodization builds up an oxide layer of Nb_2O_5 thicker than the natural layer formed in air. Due to the inference of reflected light, the color of the surface is correlated directly to the thickness of the oxide layer.

The thickness of the layer grows with 2 nm per volt. Each voltage leads to a typical color. For example, for niobium a voltage of 20 V results in a dark blue color with good contrast to other materials. Materials not affected by the electro-chemical reaction like stainless steel, brass etc. retain their original color. Aluminum shows up in different color, but the color of titanium is close to that of niobium.

The coloration of the niobium depending on the voltage is shown in Table 1.

The Nb_2O_5 layer is an electrical insulator, while the niobium has a low electrical resistivity. If the voltage is applied, the niobium piece – used as the anode – the electrical conducting solution and the cathode constitute almost a short circuit for the power supply. The current flowing in the bath has to be limited. During the forming of the pent-oxide layer, the current density reduces exponentially. The oxide layer is formed uniformly, when the current has reduced to 1/e of the starting value.

For a controlled process the power supply needs to be voltage stabilized and the maximum current flow in the beginning of the process has to be limited. Too high current densities ($j > 5$ mA/cm^2) can lead to the formation of sub-oxides (NbO, NbO_2) with completely different characteristics.

To prevent contamination of the niobium piece to be checked, the bath containers should be made of polyethylene or any other acid/alkaline resistant plastic. The power leads and contacts have to be made from Nb of reactor grade or better. Any tooling necessary in the solution should be fabricated of either polyethylene (acid/alkaline resistant plastic) or Nb of reactor grade or better.

Safety regulations for handling and storage of the acid/alkaline as well as electrical precautions have to be checked with the local authorities.

13.7.3 PROCEDURE

Solution: Two mixtures are in use for the process:

a) A mixture of deionized (DI) water (> 10 MΩcm) and nitric acid (HNO_3 in 'pro analysi/'selectipur'-quality) in a composition of 5: 1 to 9: 1.
b) A mixture of DI water (> 10 MΩcm) and ammonia-hydroxide NH_4 (OH) (in 'pro analysi/selectipur'-quality) in a composition of 5: 1.

The solution is mixed well and the temperature has to be 20 – 25 ^{0}C before starting the anodization.

The Nb pieces, cleaned by 20 μm chemical etching ("13.3") are placed in the bath and connected to the power supply. The contacts are on the backside of the surface to be checked. Within the solution Nb current leads have to be used.

The voltage of the power supply is increased from 0 to 20 V. The current flowing in the bath has to be controlled and limited to around 1 mA/cm^2. A current density of 5 mA/cm^2 must not be exceeded. At the nominal voltage of 20 V the current reduces exponentially. The current can be switched off, if it is around 0.1 mA/cm^2.

The Nb pieces are removed from the solution without touching the surface and dipped in DI water (> 10 MΩcm). Extensive rinsing under flowing DI water (> 10 MΩcm) has to be done. The rinsing and drying procedures have to be done carefully in a clean environment (cleanroom class 10000 or better). No mechanical contact to the Nb surface to be checked is allowed and no drying stains or residues of the chemical should remain on the surface.

Handling the Nb pieces during the whole process after precleaning until the completed inspection has to be done wearing latex or rubber gloves. Grease and sweat lead to chemical reactions affecting the NbO_5-layer, which gets in discolorations of the surface.

Voltage	Color
0 V	Metallic
10 V	Slightly darkened
11 – 14 V	gold – brown (varying)
16 V	Purple –red
17 –20 V	Purple changing to dark blue
20 V	Dark blue
20 – 40 V	Dark blue changing to light blue
> 40 V	Red and green colors
> 100 V	Danger of grey oxides

Table 1 Coloration of niobium by an electron-chemical anodizing process

13.8 GRINDING

Grinding of defects at the "inner" cavity surface has proven to avoid performance limitations of superconducting resonators. Grinding should be restricted to the defect area and produce a smooth surface. The pressure and velocity of the grinding wheel should be chosen so that

- no heating of the ground Nb area occurs,
- no deep scratches are produced at the ground area,
- a smooth transition is gained at the border from the ground to the untreated surface area.

Two different types of grinding tools have been successfully applied: rubberized abrasives of various shapes (cylinders, cones, thin wheels, ..) and flapped wheel (fan shaped rotating grinding paper). Two types of abrasives are commonly in use: silicon carbide and aluminum oxide (Korund). Both materials are only slowly dissolved by the Nb-chemistry ("13.3"). Therefore the size of the abrasive particles should be not larger than 50 μm. In this case any imbedded abrasive particle will be removed from the bulk Nb when etching a layer of 150 μm during final preparation of the resonator.

Recommended abrasive wheel: CRATEX, No. 545097, rubberized abrasive 120 No 83C

Recommended flapped wheel: "Pferd", abrasive size 320 or higher.

13.9 NB SPECIFICATION

The Nb sheets for half cells are specified in "Technical Specification for Niobium Applied for the Fabrication of 1.3 GHz Superconducting Cavities (RRR 300 (200)), Version D".

13.10 SURFACE CONTAMINATION

The "inner" surface of the half cell, dumb-bell and HOM coupler must be free of surface contaminations:

- Scratches deeper than 15μm
- Mechanical damage larger 15 μm
- Imprints of foreign material
- Fingerprints
- Silicon grease

13.11 CAVITY CONTOUR, FREQUENCY AND LENGTH

In the accelerator the cavity has to operate at exactly the frequency of 1300 MHz. The resonant frequency of the cavity is determined by the shape of the cells. Major parameters are the equator diameter and the length of the individual cells. The drawing of the cavity shape (drawing no 093 2214/0.000) describes the contour of the resonator as delivered. Frequency change by succeeding etching and thermal shrinkage during cool down are taken into account in the fabrication drawing.

The change of the resonance frequency by changing mechanical dimensions is given by
a) increasing the height of a half cell by extending the equator by 0.1 mm: -0.53 MHz
b) increasing the height of one half cell by extending the iris by 0.1 mm: -0.155 MHz
c) changing the contour of one half cell by uniform removal of a surface layer of 0.1 mm (as in the case of chemical etching): -1 MHz
d) increasing the total length of a 9 cell resonator in the tuning machine by equally tuning each of the 9 cells: +320 kHz/1 mm

Welding shrinkage will influence the cavity resonance according to a) and b): contour deviations are partially described by c).

The delivered cavity is tuned at DESY to establish the right resonance frequency and equal electrical excitation of the individual 9 cells. This is accomplished by slightly changing the length of the individual cells. Any deviation of the ideal cavity contour will be compensated hereby but with the consequence of changing the total cavity length. To keep the cavity length in the specified tolerance of ± 3 mm it is therefore necessary to assure strict individual tolerances. Ideally one would request a contour deviation of no more than ± 0.1 mm, which is hard to achieve. Experience with the previous production of half cells showed that there is a negative contour change (smaller volume) at the iris region whereas the equator region has a positive one. These areas are sampled by dominant electric and magnetic field, respectively, and the resultant frequency changes are of opposite sign so that the result of contour changes is cancelled to some extent. On the other hand, the other mechanical tolerances as given above might add up. Therefore the acceptable tolerances are

- ±0.1 mm for welding shrinkage,
- ±0.2 mm for contour change of the half cells.

During the last cavity production a 100 % frequency check of half cells and dumb-bells was performed and deviations of the ideal contour were detected and corrected. Measurement and calculation of the height correction is done by DESY. The correction is done by cutting the height of a cell and a dumb-bell to an intermediate length in such a way, that a too long completed cavity was shortened the right amount when tuned to the correct frequency in the 9 cell tuning machine.

Most of the cavities of the latest production stayed within the length tolerance of ± 3 mm at the design frequency of 1.3 GHz. The described tuning philosophy is based on adjusting contour errors by tuning the fundamental mode (1.3 GHz) properties. It turned out, however, that in some cavities important higher order mode frequencies were distorted too much. In most cases this was due to imperfect end half cells, thus destroying the asymmetry of the right and left end cells. For this reason all end half cells have to be measured with the 3D technique and frequency-checked before and after welding.

13.12 LIST OF DRAWINGS

The list of drawings is attached separately.

13.13 QUALITY CONTROL REQUIREMENT

The quality control requirement is attached separately.